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ORIGINAL ARTICLE

Thermodynamic analysis of triple effect LiBr-H2O vapour absorption cascaded with single/multi cascaded vapour compression refrigeration systems for low & ultra-low temperature applications

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Abstract

The Effect of performance parameters on percentage enhancement in thermal performance (COP and exergy efficiency) of triple Effect LiBr-H_2O vapour absorption cascaded compression refrigeration systems (in single and multi-staged cascaded VCRS) have been compared in this paper. The numerical computations have been carried out for triple effect Li-Br VAR system cascaded with three cascaded VCR systems using HFO, low GWP ecofriendly HFCs in medium temperature circuit and HFO, low GWP ecofriendly HFCs in intermediate temperature circuit and ecofriendly R32 and R245fa refrigerants in low temperature circuit). To validate the results obtained by developed model for triple effect Li-Br VAR system cascaded with three stage cascade refrigeration systems and energy-exergy performances have been computed for -30ºC, to -150ºC using different cascading in VCR systems and energy-exergy performance enhancements have been obtained. The effect of variation of MTC temperature (from -30ºC to -50ºC), ITC temperatures (from -50ºC to -90ºC) and LTC temperature (from -110ºC to -150ºC) on thermal performances and first and second law efficiencies (COPs and exergy efficiencies) and % enhancement have been computed. The effect of several ecofriendly refrigerants on Thermal performances in MTC Cycle have been investigated.

1. Introduction

High global warming refrigerants have found in practice in a variety of applications. The 1987 Montreal Protocol stated that some refrigerants having a higher global warming importance were degrading the ozone layer and recommended their replacement with refrigerants with a lower global warming value. The usage of R134 was outlawed by the EU on first January 2011. In cycles of VCR systems, a comparable refrigerant is R134a. In contrast to carbon dioxide, which the Montreal Prot°Col states must be phased out by 2013, R134a has a potential for 1430 global warming. As a result, automobile air conditioning systems must anticipate a new refrigerant with a lower potential for global warming [1]. Using HFO+HFC blends at a dead state temperature of 313K (40°C), a detailed thermodynamic exergy computation of simple and cascaded vapour compression refrigeration was performed. The R515A yielded the highest first law efficiency (COP) and exergy efficiency with the lowest exergy destruction ratio. Similar to this, the first law efficiency (COP Cascade) of cascaded VCR systems using HFC + HFO Blends in HT cycles and HFC + HFO Blends in LT cycles was

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calculated. Higher first law efficiency and lower exergy destruction ratio are obtained when cascaded VCR systems use R454B in HT cycles and R513A in LT cycles. Compared to utilizing R454B in the higher temperature cycle and R513A in the LT cycle, the thermodynamic performances obtained with R454B and R515 in the HT cycle and R513A in the LT cycle are marginally lower. The refrigeration systems with cascading vapour compression that use R454B during HT cycles and R454C during LT cycles yield the lowest first law efficiency as well as the highest exergy destruction ratio and energetic efficiency [2]. The energy and exergy performance of R513a, a drop-in replacement for R134a, is investigated using the economized-cycle vapor compression refrigeration system. The entire system is analysed to determine the performance differences between R513a and R134a systems in terms of capacity, COP, exergy destruction rate, and exergy efficiency [3]. At a dead state temperature of 313K (40°C), the R515A gives the highest first law efficiency, exergetic efficiency, and lowest exergy destruction ratio. This information was discovered through numerical computation of performance parameters using HFO+HFC blends as alternative refrigerants in the VCR systems at evaporator temperature of -30o and condenser temperature of 50°C at 80% of compressor efficiency. It has been claimed that cascade refrigeration systems use HFO+HFC blends to boost thermodynamic performance (COPs, work done by compressors, energy destruction ratio, mass flow rates, and heat rejected by condensers) by reaching temperatures as low as -70°C to -90°C for various applications. The first law efficiency (COP) of cascade VCR systems using R454B in HT cycle and R513A in LT cycle gives higher first law efficiency, exergetic efficiency with lowest exergy destruction ratio [4,5].

2. Vapour absorption system cascaded with single staged, multi-staged (Two staged, three staged) VCR systems

The cascade refrigeration systems are the combination of two refrigeration cycles using HFO+HFC blends having low GWP and negligible ODP, harmless to the environment, and do not violate the Kyoto Protocol. the energy and exergy performances of sixteen eco-friendly refrigerants in a two-stage VCR system to use the entropy generation principle to calculate the irreversibilities of the system and its component elements. The exergy destruction ratio (based on the exergy of product and first law efficiency in terms of COP, the second law efficiency in terms of exergetic efficiency at different input variations, and the system exergy contribution to the total work performed by the compressors) were used to numerically determine the exergy destruction ratio (EDR). It was found that HCFC 123 has the highest first-law efficiency while HFC 125 has the lowest first-law performance. R123 has the highest energy efficiency and R125 has the lowest among the sixteen eco-friendly refrigerants that were selected. The performance evaluation of cascaded refrigeration systems utilizing propylene and ethylene in LTC and HFC 152a, HC 600a, and HC 290 in HTC can be applied to replace R134a in HTC and R404a, R410a, R407c, R125, and R507a in LTC. In addition, HCFO and HFOs are utilized in HTC, whereas HCFO-1233zd(E), HFO1225ye(Z), and HFO-1336mzz(Z) are utilized in LTC to substitute R134a and R410a. R134a, R410a, and R404a can be substituted by HFO mixed blends (R450A, R515A, R513a) in HTC and (R454b and R454c) in LTC. Eco-friendly low-GWP HFC 152a, HFC 245fa, and HFC 32 in LTC can be substituted for HFC 134a in cascaded VCR systems, while R404a and R410a in LTC were recommended for all applications until 2030[6]. HFO-1234yf is a "near drop-in replacement" for HFC134a, with a 100-year GWP of 4 relatives to CO2. For applications requiring higher temperatures, R1234ze (of GWP = 6) delivers better first and second law efficiency than R1234yf (of GWP = 4). For medium- and higher-temperature applications, R1234yf and R1234ze refrigerants can be used; R134a will most likely go out of style by 2030. Using mixed-blend HFO refrigerants, which are future replacements for R404a, R410a, R407c, and R134a [5]. With a 1000 kW capacity and evaporator temperatures between −35°C and −45°C, several innovative integrated cogenerations and trigeneration configurations based on a carbon dioxide parallel compression economization-vapor compression refrigeration cycle [7]. For thermodynamic performances, the viability of utilizing an absorption solar cycle and a 105,6kW SEAC system powered by evacuated tube collectors (ETC) is suggested. In addition to developing a realistic solar cooling model that is useful for cooling service buildings, the simulation is used to choose the various system parameters and optimize them to boost solar system efficiency [8]. The absorption cycles' exergy has been calculated and discussed. Double effect parallel and series flow direct fired absorption systems with lithium bromide–water have been computed to close the knowledge gap on the energy destruction rate in the absorption system, and single to triple effect direct and indirect fired absorption cycles have been optimized for a variety of operating conditions [9,10,11]. Energy and exergy calculations were performed on a suggested hybrid system that included a triple-effect compression–absorption refrigerator and a fuel cell [12]. The results showed that the optimal cascaded vapor compression refrigeration system used R454B in the HT cycle and R513A in the LT cycle gave the highest COP and exergetic efficiency with lower power consumption in the both compressors along with the lowest system exergy destruction ratio. Eight different combinations of HFC +HFO Blends were used in the HT cycle at -30°C in the HTC evaporator, and two distinct HFC +HFO Blends (R513a and R452a) in the LT cycle. In the cascaded thermodynamic performances of vapor compression refrigeration, the lowest thermodynamic performances were noted when eco-friendly low GWP R450A refrigerants were used in higher temperature cycles and eco-friendly low GWP R454B refrigerants were used in lower temperature cycles. A cascaded vapor compression refrigeration system with a LT cycle at -90°C and a HT cycle employing R454B and R513A results in a reduced exergy destruction ratio, higher exergetic efficiency, and higher first law efficiency. When the evaporator temperature is increased, the system's first law (energy) performance (COP_cascade) and energetic performance increase as well. This was observed in the dynamic thermodynamic performances of the cascaded vapor compression refrigeration system using eco-friendly low GWP R450A refrigerant in HTC in higher temperature cycle and eco-friendly low GWP R513a refrigerant in LT cycle. First law (energy) performance (COP_cascade) is rising and exergetic performance is falling in all eight cascaded optimum vapor compression refrigeration systems when the LTC evaporator temperature is raised from -50°C to -70°C. The first law (energy) performance (COP_cascade) and exergetic performance are declining in all eight cascaded optimum vapor compression refrigeration systems when the HTC condenser temperature is raised from 40°C to 60°C. In all eight of the cascaded optimal vapor compression refrigeration systems, the exergetic performance and first law (energy) performance (COP cascade) are declining as a result of temperature overlapping increases [13]. Using fifteen eco-friendly refrigerants, including hydrocarbons, HFC and HFO, and natural refrigerants, four cascaded half effect, single effect, double effect, and triple effect lithium/bromide vapour absorption–compression refrigeration systems to produce cooling capacity at -30°C were analysed [14]. To evaluate the effectiveness of a triple-hybrid single-effect vapor absorption cooling system (VACS) powered by solar, natural gas, and auxiliary electricity-based cogeneration, building energy simulation of office building with a high capacity that is exposed to various weather conditions and the current situation emphasizes the improvements in vapour absorption refrigeration cycles. Energy-exergy analysis of the thermodynamic feasibility and practicality of an integrated solar refrigeration system that reduces irreversibilities in terms of energy destruction and losses in system components in order to improve its COP and exergetic efficiency. The study will focus on an integrated solar refrigeration system where waste heat from various energy resources supports a combined vapour absorption compression system. [16] Lithium bromide-water is used as the working fluid in this thorough exergy analysis of double effect parallel flow direct and indirect fired vapour absorption refrigeration systems. There was discussion about the parametric optimization of the temperatures in the condenser, middle generator, and main generator [17]. An innovative solar-powered multi-effect refrigeration system's thermodynamic performance. Investigated were the absorption refrigeration cycle (ARC), ejector refrigeration cycle (ERC), cascade refrigeration cycle (CRC), and solar tower system with heliostat field and central receiver (CR) that uses molten salt as the heat transfer fluid [18]. To produce hydrogen and cool the sun, The nanofluid as the working fluid in a solar parabolic trough collector (PTC) is employed with proton exchange membrane (PEM) electrolyser, thermal energy storage, Rankine cycle, triple effect absorption cooling system, and PTC are the five subsystems that make up the combined system [19].

3. Results and Discussion

Thermal model was developed for triple effect_VAR cascaded with VCRS and considered input values have been shown in the Table-1(a) & Table-1(b)respectively.

Table 1(a): input data of triple effect_VAR cascaded with VCRS

Input parameters of triple effect vapour absorption system	Value
Generator temperature	180°C
Absorber temperature	35°C
Condenser temperature	35°C
Evaporator temperature	5°C

Table-1(b): input data of Triple effect_VAR cascaded with VCRS

Performance parameters of triple effect VAR cascaded with three staged cascaded VCRS	Value
Evaporator temperature_MTC	-30
Evaporator temperature_ITC	-75°C & -90°C
Evaporator temperature_LTC	-30°C, -75°C, -90°C
LTC evaporator load	175 “kW”
Temperature overlapping_MTC	10 °C
Temperature overlapping_LTC	10 °C

3.1 Thermal performance of triple effect Li/Br VAR system

Thermal model was developed for triple effect Li/Br VAR system and thermodynamic first law energy performances and exergy efficiency (second law performance) of triple effect Li/Br-H2O VARS system have been computed using input data of table-1(a) and shown in table 2(a) respectively.

Table-2(a): Thermodynamic energy-exergy performances of triple effect_VAR cascaded with single staged VCRS

Input parameters of triple effect vapour absorption system	Value
COP	1.121
EDR	3.241
Exergy efficiency	0.2358
Exergyof generator “kW”	25.25

3.2 Effect of ecofriendly refrigerants used in single staged VCR system (for evaporator temperature=-30°C) cascaded with triple effect Li/Br VAR system

Thermodynamic first law energy performances and exergy efficiency (second law performance) of integrated triple effect Li/Br-H2O VARS system cascaded with vapour compression cascaded systems shown in table 2(b) respectively. It was observed that system using R245fa in LT cycle has highest thermodynamic performances than a cascade system- using HFC-134a in LT cycle. However cascaded system using R152a in LT cycle has highest (Best) thermodynamic energy-exergy performances than using HFC-134a in LT cycle.

Table-2(b): Improvement in the thermal performance of Triple effect_VAR cascaded with VCR system using low GWP refrigerants

Performance parameters in LTC evaporator at -30°C	R1234ze	R1234yf	R152A	R245fa	R32	R134a
First law efficiency (COP_Cascade)	1.60	1.589	1.613	1.613	1.595	1.602
% improvement in First law efficiency	42.67	41.73	43.85	43.8	42.22	42.87
Second law efficiency (Exergy Efficiency_Cascade)	0.4728	0.4666	0.4801	0.4799	0.4696	0.4738
% improvement Second law efficiency	100.4	97.88	103.6	103.5	99.16	100.9
Exergy Destruction Ratio	1.116	1.143	1.083	1.084	1.129	1.111
% Reduction in Exergy Destruction Ratio	65.56	64.72	66.59	66.55	65.16	65.73
Exergy of fuel_Cascade “kW”	43.49	43.86	43.02	43.04	43.67	43.41
Exergy of fuel_Product “kW”	20.55	20.46	20.65	20.65	20.51	20.57
Mass flow rate in VCR system “kg/sec”	0.4521	0.5150	0.2507	0.3973	0.2301	0.4040

3.3 Effect of ecofriendly refrigerants used in two staged VCR system (For evaporator temperature=-30°C) on thermodynamic energy-exergy performances of cascaded with triple effect Li/Br VAR system

Thermodynamic first law energy performances and exergy efficiency (second law performance) of integrated triple effect Li/Br-H2O VARS system cascaded with vapour compression cascaded systems of -75°C evaporator temperature has been compared and shown in table3(a)-table-3(b) respectively. It was observed that system using R245fa in LT cycle (LTC) and HFC-152a in MTC has highest thermodynamic performances than a cascade system- using HFC-245fa in medium temperature cycle and R32 in LT cycle. However cascaded system usingR152a in MTC has highest (Best) thermodynamic energy-exergy performances than using HFC-134a in MTC temperature cycle.

Table-3(a): Improvement in the thermal performance of Triple effect_VAR cascaded with VCR system using low GWP refrigerant (HFC-152a)

Performance parameters in LTC evap at -75°C	R32	R32	R245fa	R-245fa	R-32	R-32	R245fa	R-245fa
First law efficiency	1.721	1.721	1.724	1.741	1.709	1.70	1.709	1.70
% improvement in First law efficiency	53.51	53.46	53.70	55.21	52.44	51.59	54.12	53.25
Second law efficiency	0.4955	0.4952	0.4984	0.5080	0.4888	0.4835	0.5011	0.4955
% improvement Second law efficiency	110.2	110.0	111.4	115.5	107.3	105.1	112.5	110.2
Exergy Destruction Ratio	1.018	1.019	1.006	0.9684	1.046	1.068	0.9958	1.018
% Reduction in Exergy Destruction Ratio	68.59	68.55	68.95	70.12	67.73	67.04	69.28	68.59
Exergy of fuel_Cascade “kW”	63.25	63.26	62.92	62.47	63.57	63.82	62.79	63.05
Exergy of fuel_Product “kW”	31.3	31.33	31.36	31.73	31.07	30.86	31.46	31.25
Performance parameters in MTC evap at -30°C	R152a	R-245fa	R32	R-152a	R1234ze	R1234yf	R1234ze	R1234yf
First law efficiency (COP_Cascade)	1.613	1.613	1.595	1.613	1.60	1.589	1.60	1.589
% improvement in First law efficiency	43.85	43.80	42.22	43.85	42.67	41.73	42.67	41.73
Second law efficiency	0.4801	0.4798	0.4696	0.4801	0.4725	0.4666	0.4725	0.4666
% improvement Second law efficiency	103.6	103.5	99.18	103.6	100.4	97.88	100.4	97.88
Exergy Destruction Ratio	1.083	1.084	1.129	1.083	1.116	1.143	1.116	1.143
% Reduction in Exergy Destruction Ratio	66.59	66.55	65.16	66.59	65.56	64.72	65.56	64.72

Table-3(b): Improvement in the thermal performance of Triple effect_VAR cascaded with VCR system using low GWP refrigerants

Performance parameters using refrigerants in ITC at evaporator temperature=-90°C	R-245fa	R32	R32
First law efficiency (COP_Cascade)	1.605	1.589	1.577
% improvement in First law efficiency (COP_Cascade)	43.14	41.73	40.66
Second law efficiency (Exergy Efficiency_Cascade)	0.4942	0.4666	0.4740
% improvement Second law efficiency (Exergy Efficiency_Cascade)	109.6	97.88	101.0
Exergy Destruction Ratio	1.023	1.143	1.110
% Reduction in Exergy Destruction Ratio	68.43	64.72	65.76
Performance parameters using refrigerants in MTC at evaporator temperature=-30°C	R152A	R152A	R-245fa
First law efficiency (COP_Cascade)	1.613	1.613	1.613
% improvement in First law efficiency (COP_Cascade)	43.85	43.85	43.80
Second law efficiency (Exergy Efficiency_Cascade)	0.4801	0.4801	0.4801
% improvement Second law efficiency (Exergy Efficiency_Cascade)	103.6	103.6	103.5
Exergy Destruction Ratio	1.083	1.083	1.084
% Reduction in Exergy Destruction Ratio	66.59	66.59	66.55

3.4 Effect of ecofriendly refrigerants used in single staged VCR system cascaded with triple effect Li/Br VAR system

Thermodynamic first law energy performances and exergy efficiency (second law performance) of integrated triple effect Li/Br-H2O VARS system cascaded with vapour compression cascaded systems of -30°C of MTC evaporator temperature and -75°C of LTC evaporator temperature shown in table 4(a)-table-4(d) respectively. It was observed that system using R245fa in medium temperature cycle (MTC) and HFC-32 in LTC has highest thermodynamic performances than a cascade system- using HFC-245fa in medium temperature cycle and R32 in LT cycle. However cascaded system using R152a in LT cycle has highest (Best) thermodynamic energy-exergy performances than using HFC-134a in LT cycle.

Table-4(a): Improvement in the thermal performance of triple effect_VAR cascaded with VCR system using low GWP refrigerant (HFC-152a)

Performance parameters using refrigerants	R1234ze	R1234yf	R152A	R-245fa	R32	R134a	Triple effect VAR
First law efficiency	1.60	1.589	1.613	1.613	1.595	1.602	1.121
% improvement in First law efficiency	42.67	41.73	43.85	43.80	42.22	42.87	---
Second law efficiency	0.4725	0.4666	0.4801	0.4798	0.4696	0.4738	0.2358
% improvement Second law efficiency	100.4	97.88	103.6	103.5	99.18	100.9	-----
Exergy Destruction Ratio	1.116	1.143	1.083	1.084	1.129	1.111	3.241
% Reduction in Exergy Destruction Ratio	65.56	64.72	66.59	66.55	65.16	65.73	-----

Table-4(b): Improvement in the thermal performance of triple effect_VAR cascaded with VCR system using low GWP refrigerant (HFC-245fa)

Performance parameters	R-124	R-123	R141b	R407c	R410a	R227ea	Simple triple effect VAR
First law efficiency	1.606	1.619	1.630	1.533	1.590	1.570	1.121
% improvement in First law efficiency	43.21	44.40	45.32	36.69	41.76	40.05	---
Second law efficiency (Exergy	0.4759	0.4837	0.4896	0.4354	0.4668	0.4560	0.2358
% improvement Second law efficiency	101.90	105.1	107.7	84.67	97.96	93.40	-----
Exergy Destruction Ratio	1.101	1.068	1.042	1.297	1.142	1.193	3.241
% Reduction in Exergy Destruction Ratio	66.03	67.06	67.84	60.0	64.75	63.19	-----

Table-4(c): Improvement in the thermal performance of triple effect_VAR cascaded with VCR system using low GWP refrigerant (HFC-32)

Performance parameters	R404a	R507a	R236fa	R143a	R125	R134a	Triple effect VAR
First law efficiency	1.571	1.576	1.593	1.583	1.563	1.602	1.121
% improvement in First law efficiency	40.13	40.56	42.08	41.14	39.34	42.87	---
Second law efficiency	0.4565	0.4592	0.4688	0.4628	0.4516	0.4738	0.2358
% improvement Second law efficiency	93.62	94.76	98.82	96.29	91.53	100.9	-----
Exergy Destruction Ratio	1.190	1.178	1.133	1.161	1.214	1.111	3.241
% Reduction in Exergy Destruction Ratio	63.27	63.66	65.04	64.19	62.53	65.73	-----

Table-4(d): Improvement in the thermal performance of triple effect_VAR cascaded with VCR system using low GWP refrigerant (HFC-134a)

Performance parameters	R290	R600	Ethane	Propylene	R41	R134a	triple effect VAR
First law efficiency	1.60	1.612	1.504	1.60	1.552	1.602	1.121
% improvement in First law efficiency	42.65	43.74	34.10	42.71	38.38	42.87	---
Second law efficiency	0.4724	0.4794	0.420	0.4752	0.4457	0.4738	0.2358
% improvement Second law efficiency	100.4	103.3	78.14	101.6	89.03	100.9	-----
Exergy Destruction Ratio	1.117	1.086	1.381	1.104	1.244	1.111	3.241
% Reduction in Exergy Destruction Ratio	65.54	66.49	57.40	65.93	61.63	65.73	-----

The effect of MTC evaporator temperature on system thermodynamic first law energy performance and exergy efficiency (second law performance) of integrated triple effect Li/Br-H2O, VARS system cascaded with vapour compression cascaded systems of -75°C of LTC evaporator temperature shown in table 5(a)-table-5(d) respectively. It was observed that by increasing MTC evaporator temperature using R245fa in medium temperature cycle (MTC) and HFC-32 in LTC, the thermodynamic energy performances is increasing, while exergy efficiency is decreasing using all low GWP ecofriendly refrigerants and then increasing. Similarly, percentage enhancement in overall COP and percentage enhancement in overall exergy efficiency and reduction in exergy destruction ratio have been shown in 5(a)-table-5(d) respectively. When increasing MTC evaporator temperature of VCR system, the percentage enhancement in overall COP is increasing and reaching to a optimum value at -41°C of evaporator temperature and then decreasing. Similarly, percentage enhancement in overall exergy efficiency is increasing and reaching to a optimum value at -41°C of evaporator temperature and then decreasing.

Table-5(a): Improvement in the thermal performance of Triple effect_VAR cascaded with VCR system using low GWP refrigerant (HFC-152a)

Performance parameters	-50°C	-45°C	-40°C	-35°C	-30°C	-41°C (optimum)
First law efficiency	1.388	1.442	1.497	1.554	1.613	1.486
% improvement in First law efficiency	23.8	28.55	33.47	38.57	43.85	32.48
Second law efficiency	0.4822	0.4837	0.4839	0.4828	0.4801	0.4840
% improvement Second law efficiency	104.5	105.1	105.2	104.7	103.6	105.3
Exergy Destruction Ratio	1.074	1.068	1.067	1.071	1.083	1.066
% Reduction in Exergy Destruction Ratio	66.86	66.86	66.86	66.94	66.59	67.1

Table-5(b): Improvement in the thermal performance of triple effect_VAR cascaded with VCR system using low GWP refrigerant (HFC-245fa)

Performance parameters	-50°C	-45°C	-40°C	-35°C	-30°C	-38°C (optimum)
First law efficiency	1.383	1.437	1.494	1.552	1.613	1.517
% improvement in First law	23.32	28.55	33.22	38.42	43.80	35.28
Second law efficiency	0.4787	0.4810	0.4821	0.4817	0.4798	0.4821
% improvement Second law efficiency	103.0	104.1	104.5	104.3	103.5	104.5
Exergy Destruction Ratio	1.090	1.079	1.074	1.076	1.084	1.074
% Reduction in Exergy Destruction Ratio	66.38	66.71	66.86	66.81	66.50	66.86

Table-5(c): Improvement in the thermal performance of triple effect_VAR cascaded with VCR system using low GWP refrigerant (HFC-32)

Performance parameters	-50°C	-45°C	-40°C	-35°C	-30°C	-37°C (optimum)
First law efficiency	1.364	1.419	1.475	1.475	1.595	1.510
% improvement in First law efficiency	21.67	26.53	31.57	36.80	42.22	34.68
Second law efficiency	0.4664	0.4692	0.4708	0.4709	0.4696	0.4709
% improvement Second law efficiency	97.82	99.01	99.66	99.74	99.18	99.78
Exergy Destruction Ratio	1.144	1.131	1.124	1.123	1.129	1.123
% Reduction in Exergy Destruction Ratio	64.71	65.10	65.16	65.16	65.16	65.35

Table-5(d): Improvement in the thermal performance of triple effect_VAR cascaded with VCR system using low GWP refrigerant (HFC-134a)

Performance parameters	-50°C	-45°C	-40°C	-35°C	-30°C	-37°C (optimum)
First law efficiency	1.371	1.426	1.482	1.541	1.602	1.517
% improvement in First law efficiency	22.26	27.14	32.2	37.44	42.87	35.32
Second law efficiency	0.4708	0.4736	0.4751	0.4752	0.4738	0.4753
% improvement Second law efficiency	99.66	100.9	101.5	101.6	100.9	101.6
Exergy Destruction Ratio	1.124	1.112	1.105	1.104	1.111	1.104
% Reduction in Exergy Destruction Ratio	65.32	65.7	65.91	65.93	65.73	65.95

3.5 Effect of fourth staged cascaded VCR systems cascaded with triple effect Li/Br VAR system

The system thermodynamic first law energy performance and exergy efficiency (second law performance) and exergy destruction ratio of integrated triple effect Li/Br-H2O, VARS system cascaded with vapour compression cascaded systems of -90°C of ITC evaporator temperature and -50°C of MTC temperature is shown in table 6(b)-table-6(d) respectively. It was observed that by increasing LTC evaporator temperature using R152a in MTC at -50°C, R245fa in the intermediate temperature cycle(ITC) at -90°C and HFC-32 in LTC at -150°C, the overall COP_Cascade_System,and its percentage enhancement(%) overall exergy efficiency of four staged cascaded system and its percentage enhancement(%) and overall exergy destruction ratio is increasing using all low GWP ecofriendly refrigerants and its percentage reduction (%) have been shown in the Table-6(a) respectively. Similarly the COP_Cascade_Three staged _System,and its percentage enhancement(%) overall exergy efficiency of three staged cascaded system and its percentage enhancement(%) and overall exergy destruction ratio is increasing using all low GWP ecofriendly refrigerants and its percentage reduction (%) have been shown in the Table-6(a) respectively. Also the COP_Cascade_System,and its percentage enhancement(%) overall exergy efficiency of two staged cascaded system and its percentage enhancement(%) and overall exergy destruction ratio is increasing using all low GWP ecofriendly refrigerants and its percentage reduction (%) have been shown in the Table-6(a) respectively. Similarly thermal performance of Triple effect_VAR system is also shown in the Table-6(a)

Table-6(a): Improvement in the thermal performance of Triple effect_VAR cascaded with VCR system using low GWP refrigerant

Performance parameters at evaporator temperature using ecofriendly refrigerant	-150°C in LTC using R32	-90°C in ITC using R245fa	-50°C in MTC using R152a	-120°C in LTC using R32	+5°C in VAR evaporator using Li/Br H2O
First law efficiency	1.426	1.459	1.35	1.563	1.121
% improvement in First law efficiency	27.17	30.11	20.36	39.34	-
Second law efficiency	0.6261	0.5263	0.4569	0.5006	0.2358
% improvement Second law efficiency	164.7	123.7	93.79	182.6	-
Exergy Destruction Ratio	0.6023	0.8999	1.189	0.6664	3.241
% Reduction in Exergy Destruction Ratio	81.42	-	-	84.55	-

Table-6(b): Effect of varying LTC evaporator temperature on improvement in the First law thermodynamic performance (%COP) of triple effect_VAR system cascaded with three VCR systems using low GWP refrigerants

Performance parameters using R32 in LTC	-150°C	-145°C	-140°C	-135°C	-130°C
% increase in First law efficiency (COP_Cascade_LTC) using R32 in LTC	27.17	28.46	29.76	31.06	32.35
% increase in First law efficiency (COP_ Cascade ITC) using R245fa in ITC	30.11	30.11	30.11	30.11	30.11
% increase in First law efficiency (COP_ Cascade MTC) using R1234yf in MTC	20.36	20.36	20.36	20.36	20.36

The effect of LTC evaporator temperature on system thermodynamic first law energy performance and exergy efficiency (second law performance) of integrated triple effect Li/Br-H2O, VARS system cascaded with vapour compression cascaded systems of -90°C of ITC evaporator temperature and -20°C of MTC temperature is shown in table 5(b)-table-5(d) respectively. It was observed that by increasing LTC evaporator temperature using R245fa in medium temperature cycle (MTC) and HFC-32 in LTC, the exergy efficiency is increasing using all low GWP ecofriendly refrigerants

Table-6(c): Effect of varying LTC evaporator temperature on improvement in the second law thermodynamic performance (% exergy efficiency) of triple effect_VAR system cascaded with three VCR systems using low GWP refrigerants

Performance parameters using R32	-150°C	-145°C	-140°C	-135°C	-130°C
% increase in Second law efficiency (Exergy Efficiency Cascade_LTC) using R32 in LTC	164.7	168.2	171.3	174.1	176.5
% increase in Second law efficiency (Exergy Efficiency Cascade_ITC) using R245fa in ITC	123.2	123.2	123.2	123.2	123.2
% increase in Second law efficiency (Exergy Efficiency Cascade_MTC) using R1234yf in MTC	93.79	93.79	93.79	93.79	93.79

The effect of LTC evaporator temperature on system thermodynamic first law energy performance and exergy efficiency (second law performance) of integrated triple effect Li/Br-H2O, VARS system cascaded with vapour compression cascaded systems of -90°C of ITC evaporator temperature and -20°C of MTC temperature is shown in table 6(b)-table-6(d) respectively. It was observed that by increasing LTC evaporator temperature using R245fa in medium temperature cycle (MTC) and HFC-32 in LTC, the thermodynamic energy performances is increasing. The effect of LTC evaporator temperature on system exergy destruction ratio (EDR) of integrated triple effect Li/Br-H2O, VARS system cascaded with vapour compression cascaded systems of -90°C of ITC evaporator temperature and -20°C of MTC temperature is shown in table 6(b)-table-6(d) respectively. It was observed that by increasing LTC evaporator temperature using R245fa in medium temperature cycle (MTC) and HFC-32 in LTC, the system exergy destruction ratio (EDR) is increasing using all low GWP ecofriendly refrigerants.

Table-6(d): Effect of varying LTC evaporator temperature on reduction in the exergy destruction Ratio (% irreversibility ratio) of triple effect_VAR system cascaded with three VCR systems using low GWP refrigerants

Performance parameters using R32	-150°C	-145°C	-140°C	-135°C	-130°C
% Reduction in Exergy Destruction Ratio	81.42	82.06	82.63	83.12	83.53
% Reduction in Exergy Destruction Ratio	72.23	72.23	72.23	72.23	72.23
% Reduction in Exergy Destruction Ratio	63.33	63.33	63.33	63.33	63.33

Thermodynamic first law energy performances and exergy efficiency (second law performance) of integrated triple effect Li/Br-H2O VARS system cascaded with vapour compression cascaded systems of -75°C ITC evaporator temperatures have been compared at different LTC evaporator shown in table-6(e) respectively.

Table-6(e): Effect of varying LTC evaporator temperature on the first law thermodynamic performance of triple effect_VAR system cascaded with three VCR systems using low GWP refrigerants

First law efficiency	-120°C	-110°C
COP_LTC using R32	1.735	1.751
COP_ITC using R245fa	1.719	1.719
COP_MTC using R152a	1.589	1.589

Percentage enhancement in first law energy performances and percentage enhancement in exergy efficiency (second law performance) of integrated triple effect Li/Br-H2O VARS system cascaded with vapour compression cascaded systems of -75°C ITC evaporator temperature has been compared at different LTC evaporators shown in table-6(f) to table 6(h)respectively. It was observed that increasing LTC temperature (using R245fa in medium temperature cycle (MTC) and HFC-32 in LTC) the thermodynamic energy performances (COP Cascaded system) exergy performances (Exergy_Efficiency Cascaded system) in increasing while exergy destruction ratio is increasing.

Table-6(f): Effect of varying LTC evaporator temperature on improvement in the first law thermodynamic performance (% energy efficiency) of triple effect_VAR system cascaded with three VCR systems using low GWP refrigerants

LTC evaporator temperature (°C)	-120°C	-115°C	-110°C
% improvement in First law efficiency (COP_Cascade_LTC) at LTC evaporator temperature	53.27	54.7	56.14
% improvement First law efficiency (COP_Cascade_ITC) at ITC evaporator temperature =-75°C	53.25	53.25	53.25
% improvement First law efficiency (COP_Cascade_MTC) at MTC evaporator temperature =-30°C	41.73	41.73	41.73

Table-6(g): Effect of varying LTC evaporator temperature on improvement in the second law thermodynamic performance (% exergy efficiency) of triple effect_VAR system cascaded with three VCR systems using low GWP refrigerants

LTC evaporator temperature using R32	-120°C	-115°C	-110°C
% improvement in second law efficiency at LTC evaporator temperature =-120°C	158.7	160.5	162.0
% improvement second law efficiency at ITC evaporator temperature =-75°C	110.2	110.2	110.2
% improvement second law efficiency at MTC evaporator temperature =-30°C	97.88	97.88	97.88

Table-6(h): Effect of varying LTC evaporator temperature on reduction in the exergy destruction ratio (% EDR) triple effect_VAR system cascaded with three VCR systems using low GWP refrigerants

LTC evaporator temperature using R32	-120°C	-115°C	-110°C
% reduction in the exergy destruction ratio (% EDR) of LTC cycle	80.26	80.61	80.91
% reduction in the exergy destruction ratio (% EDR) of ITC cycle	68.59	68.59	68.59
% reduction in Exergy Destruction Ratio(%EDR) of MTC cycle	64.72	64.72	64.72

3.6 Effect of double staged cascaded VCR systems cascaded with triple effect Li/Br VAR system

The effect of MTC evaporator temperature on system thermodynamic first law energy performance and exergy efficiency (second law performance) of integrated triple effect Li/Br-H2O, VARS system cascaded with vapour compression cascaded systems of -75°C of LTC evaporator temperature shown in table 7(a)-table-7(d) respectively. It was observed that by increasing MTC evaporator temperature using R245fa in medium temperature cycle (MTC) and HFC-32 in LTC, the thermodynamic energy performances are increasing, while exergy efficiency is decreasing using all low GWP ecofriendly refrigerants and then increasing. The optimum MTC evaporator was found for -41°C using HFC-152a, -38°C using HFC-245fa, -37°C using HFC-32. Table-9(a) shows the optimum thermal energy-exergy performances for two staged cascaded VCR systems

Table-7(a): Improvement in the thermal performance of Triple effect_VAR cascaded with VCR system using low GWP refrigerant (HFC-152a)

Performance parameters	-50°C	-45°C	-40°C	-35°C	-30°C
First law efficiency (COP_Cascade)	1.388	1.442	1.497	1.554	1.613
% improvement in First law efficiency (COP_Cascade)	23.8	28.55	33.47	38.57	43.85
Second law efficiency (Exergy Efficiency_Cascade)	0.4822	0.4837	0.4839	0.4828	0.4801
% improvement Second law efficiency (Exergy Efficiency_Cascade)	104.5	105.1	105.2	104.7	103.6
Exergy Destruction Ratio	1.074	1.068	1.067	1.071	1.083
% Reduction in Exergy Destruction Ratio	66.86	66.86	66.86	66.94	66.59

Table-7(b): Improvement in the thermal performance of Triple effect_VAR cascaded with VCR system using low GWP refrigerant (HFC-245fa)

Performance parameters	-50°C	-45°C	-40°C	-35°C	-30°C
First law efficiency (COP_Cascade)	1.383	1.437	1.494	1.552	1.613
% improvement in First law efficiency (COP_Cascade)	23.32	28.55	33.22	38.42	43.80
Second law efficiency (Exergy Efficiency_Cascade)	0.4787	0.4810	0.4821	0.4817	0.4798
% improvement Second law efficiency	103.0	104.1	104.5	104.3	103.5
Exergy Destruction Ratio	1.090	1.079	1.074	1.076	1.084
% Reduction in Exergy Destruction Ratio	66.38	66.71	66.86	66.81	66.50

Table-7(c): Improvement in the thermal performance of triple effect_VAR cascaded with VCR system using low GWP refrigerant (HFC-32)

Performance parameters	-50°C	-45°C	-40°C	-35°C	-30°C
First law efficiency (COP_Cascade)	1.364	1.419	1.475	1.475	1.595
% improvement in First law efficiency (COP_Cascade)	21.67	26.53	31.57	36.80	42.22
Second law efficiency (Exergy Efficiency_Cascade)	0.4664	0.4692	0.4708	0.4709	0.4696
% improvement Second law efficiency	97.82	99.01	99.66	99.74	99.18
Exergy Destruction Ratio	1.144	1.131	1.124	1.123	1.129
% Reduction in Exergy Destruction Ratio	64.71	65.10	65.16	65.16	65.16

Table-7(d): Improvement in the thermal performance of triple effect VAR cascaded with VCR system using low GWP refrigerant (HFC-134a)

Performance parameters	-50°C	-45°C	-40°C	-35°C	-30°C
First law efficiency (COP_Cascade)	1.371	1.426	1.482	1.541	1.602
% improvement in First law efficiency (COP_Cascade)	22.26	27.14	32.2	37.44	42.87
Second law efficiency (Exergy Efficiency_Cascade)	0.4708	0.4736	0.4751	0.4752	0.4738
% improvement Second law efficiency	99.66	100.9	101.5	101.6	100.9
Exergy Destruction Ratio	1.124	1.112	1.105	1.104	1.111
% Reduction in Exergy Destruction Ratio	65.32	65.7	65.91	65.93	65.73

3.7 Effect of three staged cascaded VCR systems cascaded with triple effect Li/Br VAR system

The effect of MTC evaporator temperature on system thermodynamic first law energy performance and exergy efficiency (second law performance) of integrated triple effect Li/Br-H2O, VARS system cascaded with vapour compression cascaded systems of -75°C of LTC evaporator temperature shown in table 8(a)-table-8(d) respectively. It was observed that by increasing MTC evaporator temperature using R245fa in medium temperature cycle (MTC) and HFC-32 in LTC, the thermodynamic energy performances is increasing, while exergy efficiency is decreasing and then increasing using all low GWP ecofriendly refrigerants. The optimization was carried out for triple effect Li/Br -H2O) system cascaded with two staged and three staged Cascaded VCR systems.The optimum MTC evaporator was found from Table-9(a) and Table-9(b) The optimum MTC evaporator was found for -41°C using HFC-152a, -38°C using HFC-245fa, -37°C using HFC-32 in two staged cascaded VCR with triple effect VAR system. Similarly, Table-9(b) shows the optimum thermal energy-exergy performances for three staged cascaded VCR systems.

Table-8(a): Improvement in the thermal performance of Triple effect_VAR cascaded with VCR system using low GWP refrigerant (HFC-152a)

Thermal performance parameters	-50°C	-45°C	-40°C	-35°C	-30°C
First law efficiency (COP_Cascade)	1.388	1.442	1.497	1.554	1.613
% improvement in First law efficiency (COP_Cascade)	23.8	28.55	33.47	38.57	43.85
Second law efficiency (Exergy Efficiency_Cascade)	0.4822	0.4837	0.4839	0.4828	0.4801
% improvement Second law efficiency	104.5	105.1	105.2	104.7	103.6
Exergy Destruction Ratio	1.074	1.068	1.067	1.071	1.083
% Reduction in Exergy Destruction Ratio	66.86	66.86	66.86	66.94	66.59

Table-8(b): Improvement in the thermal performance of Triple effect_VAR cascaded with VCR system using low GWP refrigerant (HFC-245fa)

Thermal performance parameters	-50°C	-45°C	-40°C	-35°C	-30°C
First law efficiency (COP_Cascade)	1.383	1.437	1.494	1.552	1.613
% improvement in First law efficiency (COP_Cascade)	23.32	28.55	33.22	38.42	43.80
Second law efficiency (Exergy Efficiency_Cascade)	0.4787	0.4810	0.4821	0.4817	0.4798
% improvement Second law efficiency	103.0	104.1	104.5	104.3	103.5
Exergy Destruction Ratio	1.090	1.079	1.074	1.076	1.084
% Reduction in Exergy Destruction Ratio	66.38	66.71	66.86	66.81	66.50

Table-8(c): Improvement in the thermal performance of triple effect_VAR cascaded with VCR system using low GWP refrigerant (HFC-32)

Thermal performance parameters	-50°C	-45°C	-40°C	-35°C	-30°C
First law efficiency (COP_Cascade)	1.364	1.419	1.475	1.475	1.595
% improvement in First law efficiency	21.67	26.53	31.57	36.80	42.22
Second law efficiency (Exergy Efficiency_Cascade)	0.4664	0.4692	0.4708	0.4709	0.4696
% improvement Second law efficiency	97.82	99.01	99.66	99.74	99.18
Exergy Destruction Ratio	1.144	1.131	1.124	1.123	1.129
% Reduction in Exergy Destruction Ratio	64.71	65.10	65.16	65.16	65.16

Table-8(d): Improvement in the thermal performance of triple effect_VAR cascaded with VCR system using low GWP refrigerant (HFC-134a)

Performance parameters	-50°C	-45°C	-40°C	-35°C	-30°C
First law efficiency (COP_Cascade)	1.371	1.426	1.482	1.541	1.602
% improvement in First law efficiency (COP_Cascade)	22.26	27.14	32.2	37.44	42.87
Second law efficiency (Exergy Efficiency_Cascade)	0.4708	0.4736	0.4751	0.4752	0.4738
% improvement Second law efficiency	99.66	100.9	101.5	101.6	100.9
Exergy Destruction Ratio	1.124	1.112	1.105	1.104	1.111
% Reduction in Exergy Destruction Ratio	65.32	65.7	65.91	65.93	65.73

Table-9(a): Optimum thermal performance of triple effect_VAR cascaded with two staged cascaded VCR system using low GWP refrigerants for replacing HFC-134a

Optimum thermal performance parameters	-41°C using HFC-152a	-38°C using HFC-245fa	-37°C using HFC-32	-37°C using HFC-134a
First law efficiency (COP_Cascade)	1.486	1.517	1.510	1.517
% improvement in First law efficiency	32.48	35.28	34.68	35.32
Second law efficiency	0.4840	0.4821	0.4709	0.4753
% improvement Second law efficiency	105.3	104.5	99.78	101.6
Exergy Destruction Ratio	1.066	1.074	1.123	1.104
% Reduction in Exergy Destruction Ratio	67.1	66.86	65.35	65.95

Table-9(b): Optimum thermal performance of triple effect_VAR cascaded with three staged cascaded VCR system using low GWP refrigerants for replacing HFC-134a

Optimum thermal performance parameters	-41°C using HFC-152a	-38°C using HFC-245fa	-37°C using HFC-32	-37°C using HFC-134a
First law efficiency (COP_Cascade)	1.486	1.517	1.510	1.517
% improvement in First law efficiency	32.48	35.28	34.68	35.32
Second law efficiency (Exergy Efficiency_Cascade)	0.4840	0.4821	0.4709	0.4753
% improvement Second law efficiency	105.3	104.5	99.78	101.6
Exergy Destruction Ratio	1.066	1.074	1.123	1.104
% Reduction in Exergy Destruction Ratio	67.1	66.86	65.35	65.95

Table-9(c): Optimum thermal performance of triple effect_VAR cascaded with VCR system using low GWP refrigerants for replacing HFC-134a

Optimum thermal performance parameters	-41°C using HFC-152a	-38°C using HFC-245fa	-37°C using HFC-32	-37°C using HFC-134a
First law efficiency (COP_Cascade)	1.486	1.517	1.510	1.517
% improvement in First law efficiency (COP_Cascade)	32.48	35.28	34.68	35.32
Second law efficiency (Exergy Efficiency_Cascade)	0.4840	0.4821	0.4709	0.4753
% improvement Second law efficiency	105.3	104.5	99.78	101.6
Exergy Destruction Ratio	1.066	1.074	1.123	1.104
% Reduction in Exergy Destruction Ratio	67.1	66.86	65.35	65.95

4. Conclusions

Following conclusions were drawn from triple effect VAR system cascaded three stage cascaded refrigeration systems.

- Triple effect VAR system cascaded with VCR system using R245fa in LT cycle has highest thermodynamic performances than a cascade system- using HFC-134a in LT cycle. However cascaded system using R152a in LT cycle has highest (Best) thermodynamic energy-exergy performances than using HFC-134a in LT cycle.
- Triple effect VAR system cascaded with VCR system using R245fa in LT cycle (LTC) and HFC-152a in MTC has highest thermodynamic performances than a cascade system- using HFC-245fa in medium temperature cycle and R32 in LT cycle. However cascaded system usingR152a in MTC has highest (Best) thermodynamic energy-exergy performances than using HFC-134a in MTC temperature cycle.
- Integrated triple effect VAR system cascaded with VCR system using R245fa in medium temperature cycle (MTC) and HFC-32 in LTC has highest thermodynamic performances than a cascade system- using HFC-245fa in medium temperature cycle and R32 in LT cycle. However cascaded system using R152a in LT cycle has highest (Best) thermodynamic energy-exergy performances than using HFC-134a in LT cycle.
- By increasing MTC evaporator temperature of VCR system, the percentage enhancement in overall COP is increasing and reaching to a optimum value at -41°C of evaporator temperature and then decreasing. Similarly, percentage enhancement in overall exergy efficiency is increasing and reaching to a optimum value at -41°C of evaporator temperature and then decreasing.

- By increasing LTC temperature (using R245fa in medium temperature cycle (MTC) and HFC-32 in LTC) in the triple effect_VAR system cascaded with three cascaded VCR systems the thermodynamic energy performances (COP Cascaded system) exergy performances (Exergy Efficiency Cascaded system) in increasing while exergy destruction ratio is increasing.
- The optimum MTC evaporator in the double staged cascaded VCR systems cascaded with triple effect Li/Br VAR system was found for -41°C using HFC-152a, -38°C using HFC-245fa, -37°C using HFC-32.
- By increasing MTC evaporator temperature of three staged cascaded VCR systems cascaded with triple effect VAR system using R245fa in medium temperature cycle (MTC) and HFC-32 in LTC, the thermodynamic energy performances is increasing, while exergy efficiency is decreasing and then increasing using all low GWP ecofriendly refrigerants.
- The optimum MTC evaporator was found for -41°C using HFC-152a, -38°C using HFC-245fa, -37°C using HFC-32 in two staged cascaded VCR with triple effect VAR system.

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